Period Changes of the LMC Cepheids Determined from the Harvard, OGLE and ASAS Data

P a w e l   P i e t r u k o w i c z

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ABSTRACT

Observations of Cepheids in the Large Magellanic Cloud, made over the last several decades, allow us to search for evolutionary period changes. None of the Cepheid from our sample of 378 stars stopped pulsating. Also none of them showed a large period change which could indicate mode switching. However for Cepheids with $\log P > 0.9$ we found significant period changes, positive as well as negative. A comparison between the observed period changes and theoretical predictions shows moderate agreement with some models (Bono et al. 2000), and a very large disagreement with others (Alibert et al. 1999). The large differences between the models are likely caused by the very high sensitivity of stellar evolution during core helium burning phase to even small changes in the input physics, as discovered by Lauterborn, Refsdal and Weigert (1971).

Galaxies: Magellanic Clouds – Stars: Cepheids – Stars: evolution

1   Introduction

The Period - Luminosity relation of the Cepheids is one of the most fundamental tools for estimating distances in the Universe. Various observations of Cepheids provide tests for models of stellar structure, evolution and pulsation.

Cepheids are Population I stars undergoing core helium burning. They pulsate while crossing the instability strip in the Hertzsprung–Russel diagram at the effective temperature $\log T_{\text{eff}} \approx 3.8$. There is also a possibility of observing a Cepheid during the first crossing of the strip, when the star is in the Hertzsprung gap and evolves on a thermal time scale.

While a star crosses the instability strip its pulsation period changes. This happens slowly even for massive stars. Hence a long time interval is needed to detect the changes. Some Cepheids in our Galaxy were observed for almost 200 years. The recent results of these studies were published by Berdnikov and Ignatova (2000), who compiled the observations of δ Cep, η

Aql and ζ Gem, all showing very strong period changes. Also Turner (1998) presented data on period changes of 137 northern hemisphere Cepheids. A quantitative relation between the observed changes and those predicted by the evolutionary models was investigated long time ago by Hofmeister (1967). Recently Macri, Sasselov and Stanek (2001) reported on a dramatic change in the light curve of a Cepheid discovered by E. Hubble in M33. They suggest that the star stopped pulsating.

The Magellanic Clouds have very many known Cepheids, and a large data set with their periods was published for the LMC by Payne-Gaposchkin (1971). These are the results of Harvard photographic observations made in the years: 1910 – 1950. Deasy and Wayman (1985) found that about 40 percent of a sample of 115 stars showed period variations, apparently too rapid to be explained with the evolutionary models. In the late 1990's a very large amount of CCD photometry for the Magellanic Cloud Cepheids was obtained by several groups searching for gravitational microlensing.

The goal of this paper is to determine period changes in the LMC Cepheids comparing the data published by Payne-Gaposhkin (1971) with the results of two recent projects: OGLE (the Optical Gravitational Lensing Experiment, Udalski et al. 1997), and ASAS (the All Sky Automated Survey, Pojmański 2000). We also compare the observed period changes with the predictions of the recent stellar evolutionary models.

2   Observational Data

A digital version of the Payne-Gaposchkin (1971) data was kindly provided to us by Dr. David Bersier. All 1110 Cepheids have their HV (Harvard Variable) numbers. The positions are given in H. Leavitt's coordinates. The moments of maxima correspond to the best observed epochs, and the periods were estimated with the data spanning almost 50 years. There are also useful remarks about some stars, like a doubtful period or a light curve with a large scatter, and the information about previously measured period. Contemporary data for the fainter Cepheids are taken from OGLE-II project (Udalski et al. 1999), while for the brightest stars they were obtained from the ASAS project (Pojmański 2000).

The OGLE and Harvard databases were matched using 2000.0 coordinates. For each Cepheid from Harvard list, which should be in one of 21 OGLE fields, we looked for an OGLE Cepheid in a square 40" on a side. If there were more than one star in the square, we chose that with a very

close period. We identified 368 stars that way. Three Cepheids were not found. HV 900 is too bright for OGLE camera (it is saturated). HV 970 and HV 13032 are very faint in Harvard catalogue (average magnitudes are 16.84 and 16.70 respectively) and the period is uncertain. There were some problems with HV 5651. Probably there is an error in the declination of this star in Payne-Gaposchkin's database. The ASAS provided data for 11 brightest Cepheids. We had a total of 379 stars for further analysis.

To be sure that stars were matched correctly we compared the magnitudes (Fig. 1) and coordinates (Fig. 2) obtained from the Harvard catalogue and from the OGLE or ASAS catalogs. We rejected the star HV 5761. It is blended with a close companion.

We note that among the remaining 378 Cepheids 29 are the first overtone pulsators and one is a double mode (fundamental and first overtone) pulsator. Cross-correlations of each variable and its parameters are available on the Internet at ftp://ftp.astrouw.edu.pl:/pub/pietruk/ceph.tab

3   Evolutionary models of Cepheids

A recent theoretical survey of Cepheids' characteristics for a number of evolutionary models was published by ABHA (Alibert, Baraffe, Hauschildt, Allard 1999). It contains parameters of stars at the blue and red edges of the instability strip for models in the ZAMS mass range $2.75 - 12M_\odot$ with three chemical compositions: $(Z, Y) = (0.02, 0.28)$, $(0.01, 0.25)$ and $(0.004, 0.25)$, representative of the Galaxy, LMC and SMC, respectively.

Other theoretical models were recently published by Bono et al. (2000). They adopted the same metallicities as ABHA but slightly different helium contents: $(Z, Y) = (0.02, 0.27)$, $(0.01, 0.255)$ and $(0.004, 0.23)$. Bono et al. gave the duration for every crossing of the instability strip, but they gave the fundamental mode periods at the middle of the strip only.

There are some general properties of all evolutionary models. For a given crossing of the instability strip the periods at the red edge are larger than those at the blue edge by an average factor 1.6. The mean period, and the luminosity, increase with the stellar mass. For a given chemical composition a star with a mass below certain value has the evolutionary loop too small to enter the instability strip. A star with a somewhat larger mass enters the instability strip, but the maximum effective temperature reached in the loop phase is within the strip, i.e. such stars enter and exit the instability strip through its red edge. Finally, still more massive stars cross the full

strip twice during their loop phase of evolution: first from the red to the blue, and next they return from the blue to the red.

For these most massive stars there are three crossing through the instability strip: I, II, III, with the first referring to the very rapid crossing of the Hertzsprung gap during the evolution following hydrogen exhaustion in the core, and towards helium ignition in the core. During this first crossing the pulsation period increases rapidly. During the much slower loop phase the pulsation period decreases in crossing II, and it increases again in crossing III, while the star burns helium in the core and hydrogen in the shell.

Using the data from ABHA and Bono et al. tables we plotted in Fig. 3 the crossing times as a function of period for Z = 0.01. It is clear that models agree well for crossings I, but they disagree by up to two orders of magnitude for the crossings II and III. This is likely the consequence of the phenomenon discovered decades ago by Lauterborn, Refsdal and Weigert (1971), who found that stellar structure and evolution during the core helium burning phase is very sensitive to even small changes in the input physics.

Since we have values of the pulsation periods P_0 and P_1 in two moments of time t_0 and t_1 respectively (at the strip edges), we define the theoretical rate of period change as

$$r_{th} \equiv \frac{\Delta P}{\Delta t} \frac{1}{P^2} = \frac{P_1 - P_0}{t_1 - t_0} \frac{1}{P^2} \tag{1}$$

The scaling is chosen so that all model results of ABHA can be presented in Fig. 4, which displays the rates of period change as a function of period for three metallicities. The crossing I is well separated from II and III, as the star is crossing the Hertzsprung gap on a thermal time scale.

4   Comparison with the data

We calculate the rate of observational period change using the equation

$$r_{obs} \equiv \frac{\Delta P}{\Delta t} \frac{1}{P_1^2} = \frac{P_1 - P_0}{t_1 - t_0} \frac{1}{P_1^2} \tag{2}$$

where P_0 is the old (Harvard) period at the moment of Cepheid light curve maximum t_0, and P_1 is the new (OGLE or ASAS) period at the moment of maximum t_1. We estimate the uncertainty of the rate of period change using the relation:

$$\sigma_{obs} \approx \frac{\sigma_{P_1}}{t_1 - t_0} \frac{1}{P_1^2} \tag{3}$$

where σ_{P_1} is the estimated error of the period as given by OGLE or ASAS. Unfortunately, the error estimates of the Harvard periods, σ_{P_0}, were not given by Payne-Gaposchkin. Therefore, σ_{obs} is the lower bound of the observational error of the rate. However, the periods determined from Harvard data are generally of high accuracy, as they are based on the observations covering several decades. Hence, the real σ_{obs} is not likely to be much larger than the estimate given with the eq. (3). We neglected the contribution of t_0 and t_1 uncertainties to the error balance.

The errors of OGLE periods were given as $\sigma_{P_1} = 7 \times 10^{-5}$ P_1 by Udalski et al. (1999). The corresponding errors for ASAS variables were kindly calculated by Dr. Laurent Eyer using Hipparcos software.

Fig. 5 presents the ratio of the variance of the observed distribution of the measured period changes σ_{dist} to the the average nominal observational error σ_{obs} defined with the eq. (3). We binned Cepheids into three period groups. Only the group with the longest periods, $\log P > 0.9$, has measurable period changes between the epoch of Harvard observations and the present observations of OGLE and ASAS. Figs. 6 and 7, display a comparison between the rates of period change as observed for long period Cepheids, and the two sets of theoretical models, ABHA and Bono et al., respectively. It is clear that some observed rates are significant, i.e. much larger than their nominal errors, and some are not significant. It is also clear that the ABHA models for $Z = 0.01$ (corresponding to LMC Cepheids) predict the rates of period change which are much larger than observed, while the rates predicted by Bono et al. are comparable to the observed rates.

Bono et al. (2000) do not provide all the data we needed for Fig. 7. We assumed that the period change, $\dot{P}$, is constant during the model crossing the instability strip. The lines in Fig. 7 correspond to the variation of period in the denominator of the formula $\dot{P}/P^2$ between the two edges of the instability strip, assuming that the ratio of periods at the red to the blue edges is 1.6.

5   Other evolutionary effects

The OGLE photometry was done in B, V, and I bands. Also, the estimate of interstellar reddening was provided for each star. Fig. 8 presents the color-period relation, where the $(V - I)_0$ index was corrected for the reddening (Udalski et al. 1999). A slope of the instability strip, as well as its width are clearly apparent. The models of ABHA predicted that the stellar evolution

is much faster near the red edge of the instability strip than near the blue edge. Therefore, we calculated $\delta(V-I)_0$, which is the difference between the measured value of $(V-I)_0$, and the value corresponding to the straight line drawn in Fig. 8 through the middle of the instability strip. The ABHA models predict that there should be a correlation between the $\delta(V-I)_0$ parameter and the absolute value of the observed rate of period change, $|\dot{P}/P^2|$: the redder the star, the more rapid the period change should be. The observed diagram is shown in Fig. 9 for Cepheids with measurable rate of period change, i.e. those with $\log P > 0.9$. There is no apparent correlation.

6   Discussion

There are several important conclusions following from our analysis. None of 378 Cepheids has left the instability strip or changed the pulsating mode during several decades separating Harvard, OGLE and ASAS observations. This is consistent with the probability for these processes. We can estimate the probability of leaving the strip in a time interval of up to 100 years. The time it takes to cross the instability strip is approximately given as $|P/\dot{P}|$, which is observed to be $\sim 3 \times 10^5$ years for $P = 10$ days, and $\sim 3 \times 10^4$ years for $P = 100$ days (cf. Fig. 6 and 7). Therefore, the probability that a star with a period in the range $10 - 100$ days (for which $\dot{P}$ values are measurable) would get out of the instability strip in just 100 years is only $\sim 10^{-3}$. For shorter period Cepheids the evolutionary time scales are longer and the corresponding probabilities are even smaller.

Deasy and Wayman (1985) noticed that the observed period changes were more rapid than expected according to the models popular at that time. We find that the observed period changes are slower than predicted by the ABHA models and about as rapid as expected by Bono et al. (2000). Note: in principle many factors may contribute to period changes (like mixing or He content), so the evolutionary predictions should provide a lower limit to what is observed. Clearly, the predictions of the ABHA models cannot be right.

A histogram of Cepheid periods resulting from ABHA models predicts too few long period Cepheids, or there are too many long period Cepheids observed in the Magellanic Clouds. This discrepancy, noted by ABHA, is a direct consequence of the too rapid evolution of their models across the instability strip during the loop phase leading to too rapid period changes

and too short lifetimes, and hence too few Cepheids.

It is surprising that we have not found any star undergoing the first crossing of the instability strip. The model evolutionary time scales corresponding to the first crossing are reliable, as these are simply thermal time scales. Indeed, the two sets of models agree with each other (cf. triangles in Fig. 3). The empirical crossing time scales for the loop phase are between $\sim 3 \times 10^4$ and 3×10^5 years (previous paragraph), while the first crossing time scales are expected to be $\sim 4 \times 10^3$ years for the long period Cepheids, i.e. only a factor of ~ 25 shorter. With the large number of observed Cepheids we would expect to find some with large $\dot{P}$ values, corresponding to the first crossing. Yet, the most rapid period change observed is negative, i.e. it cannot correspond to the first crossing (note the point close to the lower edge of Fig. 6 and Fig. 7, at $\log P \approx 1.3$).

The observational data could be considerably corrected. If the Harvard photometric data were available it would be possible to phase together the old and the modern photometric measurements, improving considerably the observational estimates of period changes, and providing more reliable estimates of their errors. However, even with the results as presented in this paper there is a clear need to refine theoretical models.

Note that neither ABHA nor Bono et al. (2000) models cover the longest period Cepheids, i.e. the brightest and the most massive stars. It would be very useful to extend model calculations to masses large enough to account for Cepheids with periods up to 130 days.

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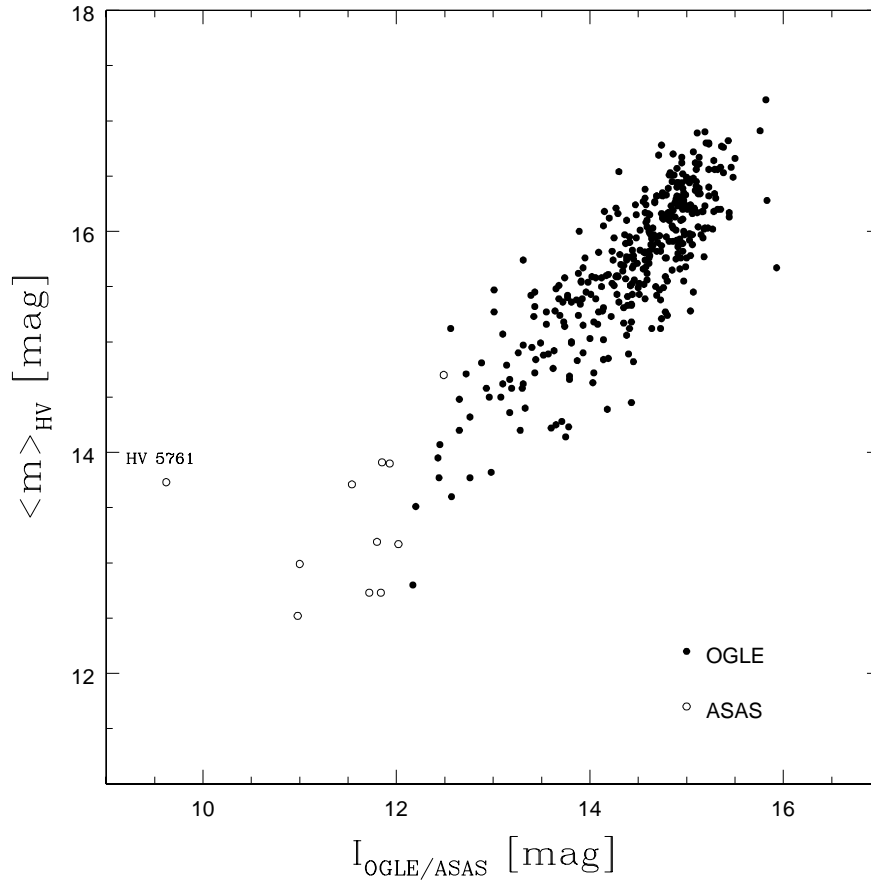
Fig. 1. A comparison between the average Harvard magnitudes and I-band OGLE and ASAS magnitudes for 379 Cepheids in the Large Magellanic Cloud. Notice the anomalous location of HV 5761.
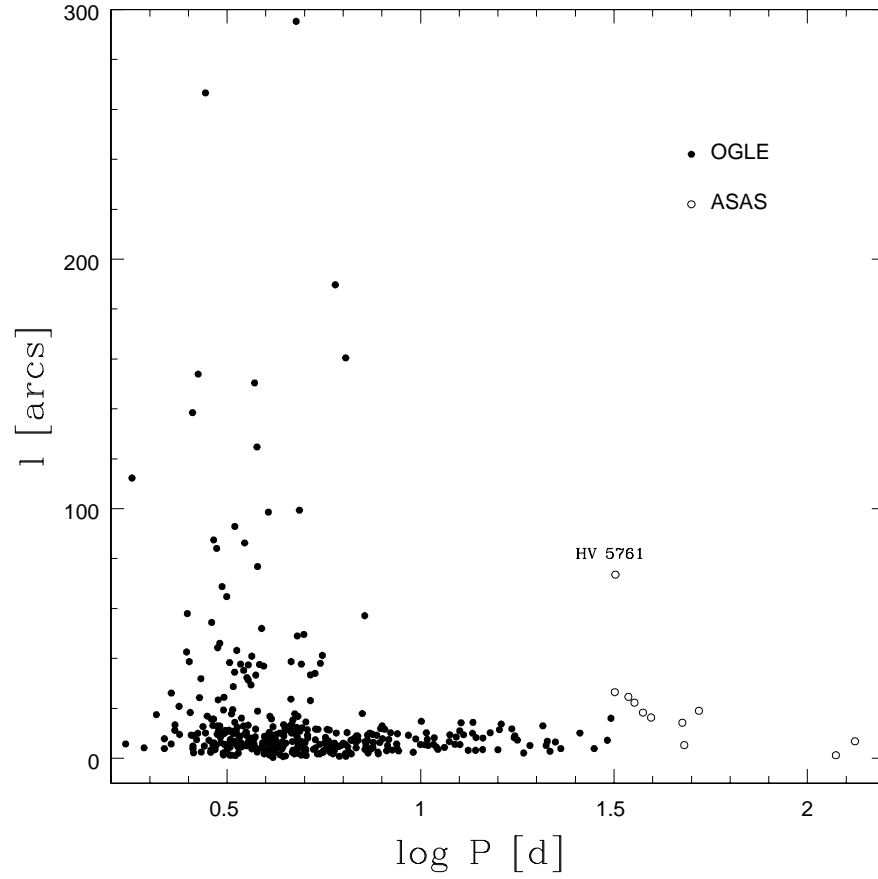
Fig. 2. The difference in coordinates (in arcsecs) between the Harvard catalog and the OGLE and ASAS catalogs is shown as a function of period. The positions are in a very good agreement for bright stars, with $\log P > 0.9$. Notice the anomalous location of HV 5761.
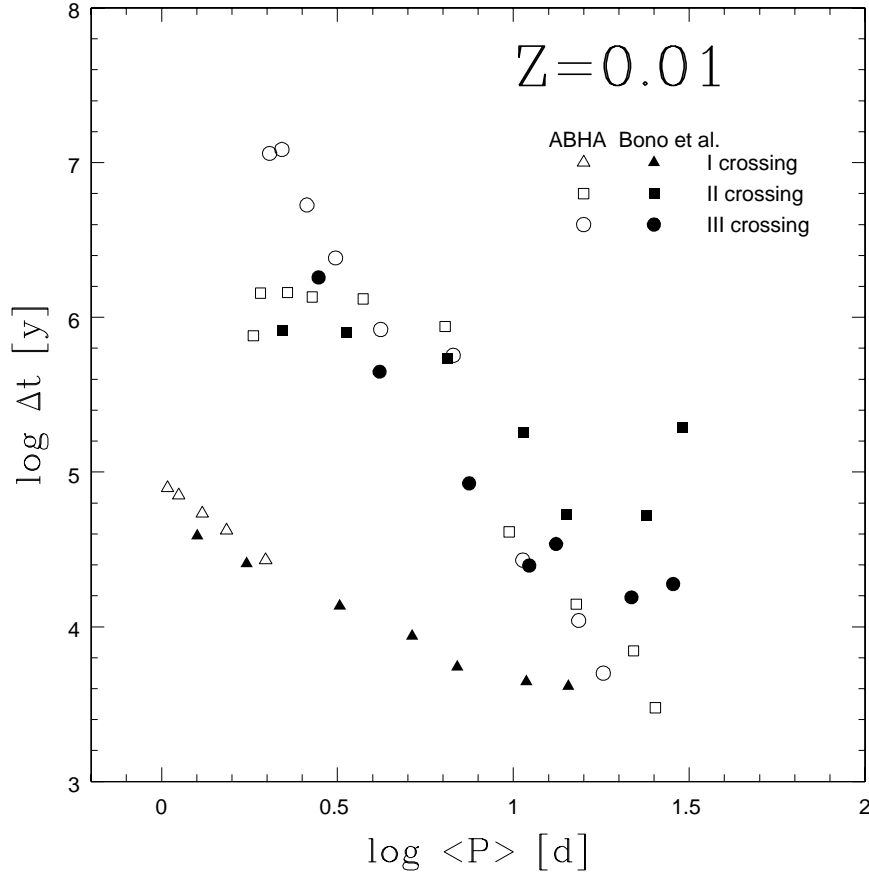
Fig. 3. Crossing time of the instability strip as a function of Cepheid period according to two theoretical paper: ABHA (Alibert, Baraffe, Hauschildt, Allard 1999) and Bono et al. (2000). Different symbols correspond to the three crossings of the instability strip. Notice that the two sets of models agree well for the first crossing, which is fast, on a thermal time scale. The agreement is very poor for the second and third crossings, which are relatively slow, corresponding to the evolution in the loop phase.
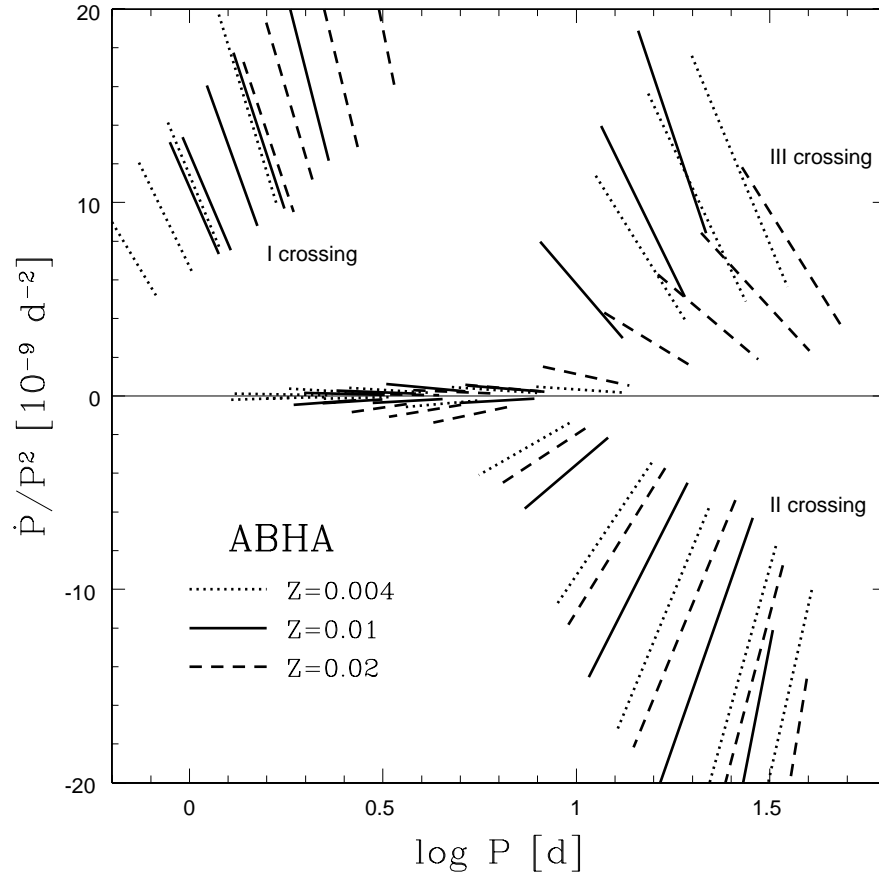
Fig. 4. The rate of period changes predicted for the three crossings of Cepheid instability strip is show as a function of period according to the models calculated by ABHA (Alibert, Baraffe, Hauschildt, Allard 1999).
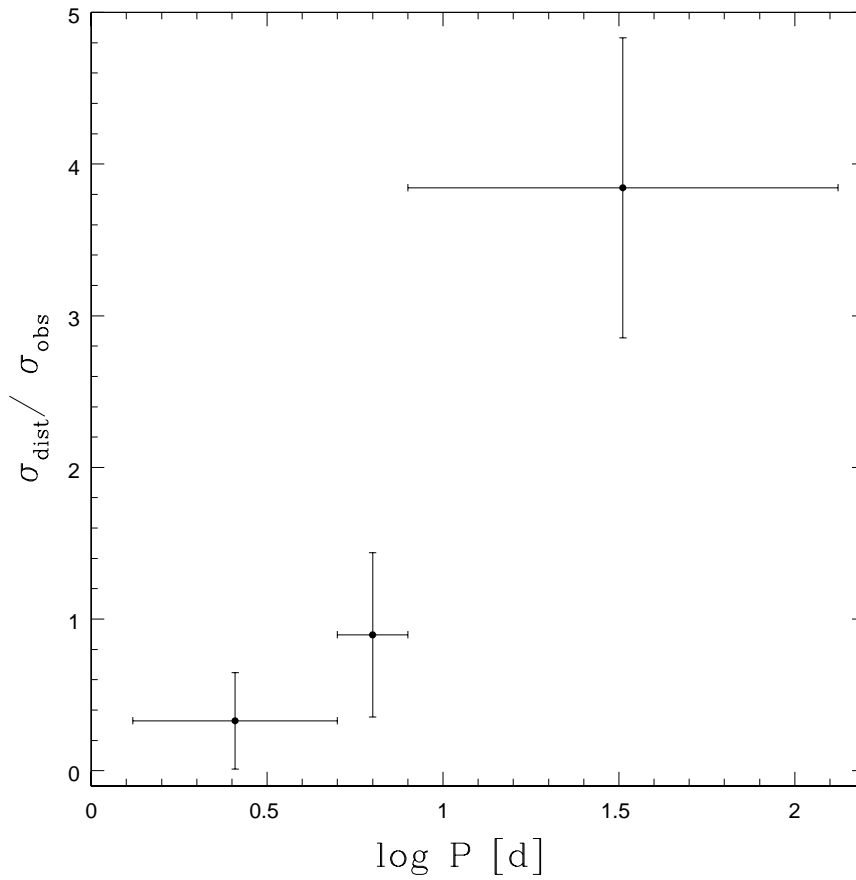
Fig. 5.— The ratio of the observed scatter in the measured period changes σ_{dist} to the nominal observational error σ_{obs} is shown for three groups of Cepheid periods. It is clear that only the group with the longest periods, $\log P > 0.9$, has measurable period changes between the epoch of Harvard observations, and present as observed by OGLE and ASAS.
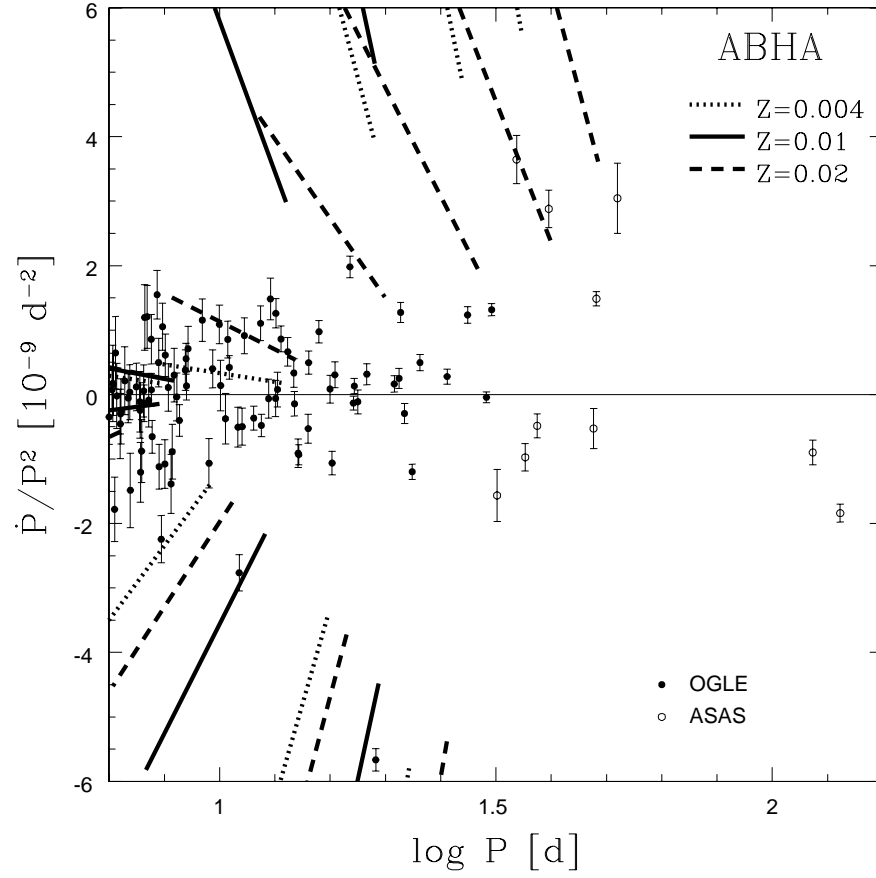
Fig. 6.   A comparison between the period changes predicted for Cepheids with long periods by ABHA (Alibert, Baraffe, Hauschildt, Allard 1999) and the Harvard, OGLE and ASAS observations. The disagreement is striking.
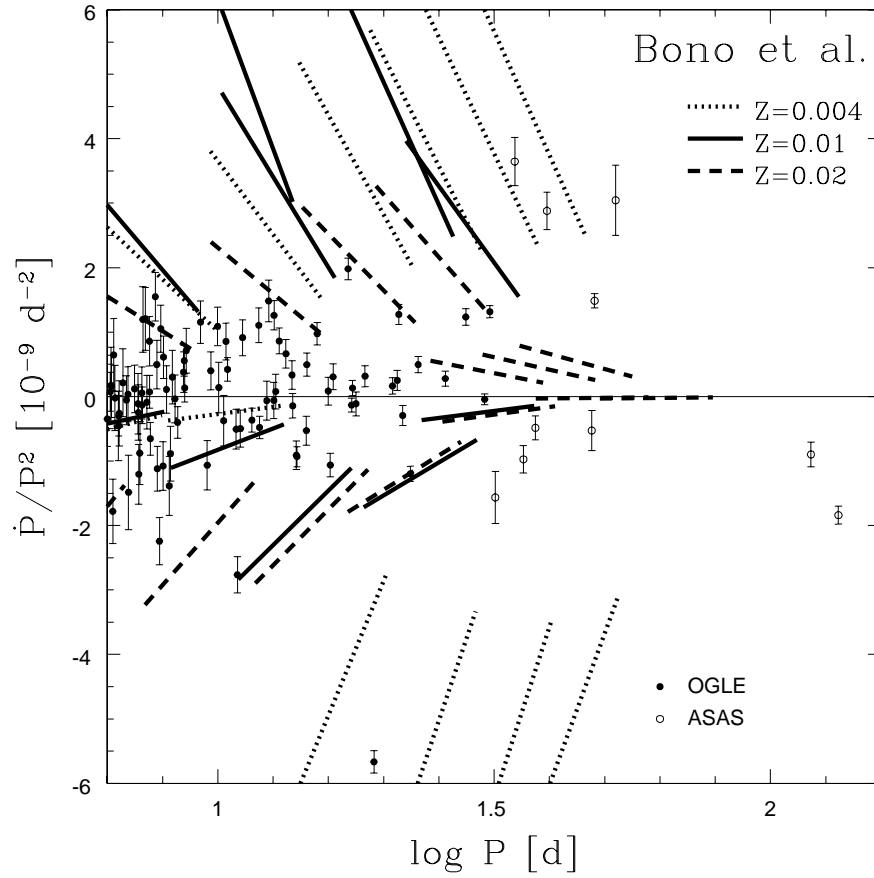
Fig. 7. A comparison between the period changes predicted for Cepheids with long periods by Bono et al. (2000) and the Harvard, OGLE and ASAS observations. The models and the observations are in approximate agreement.
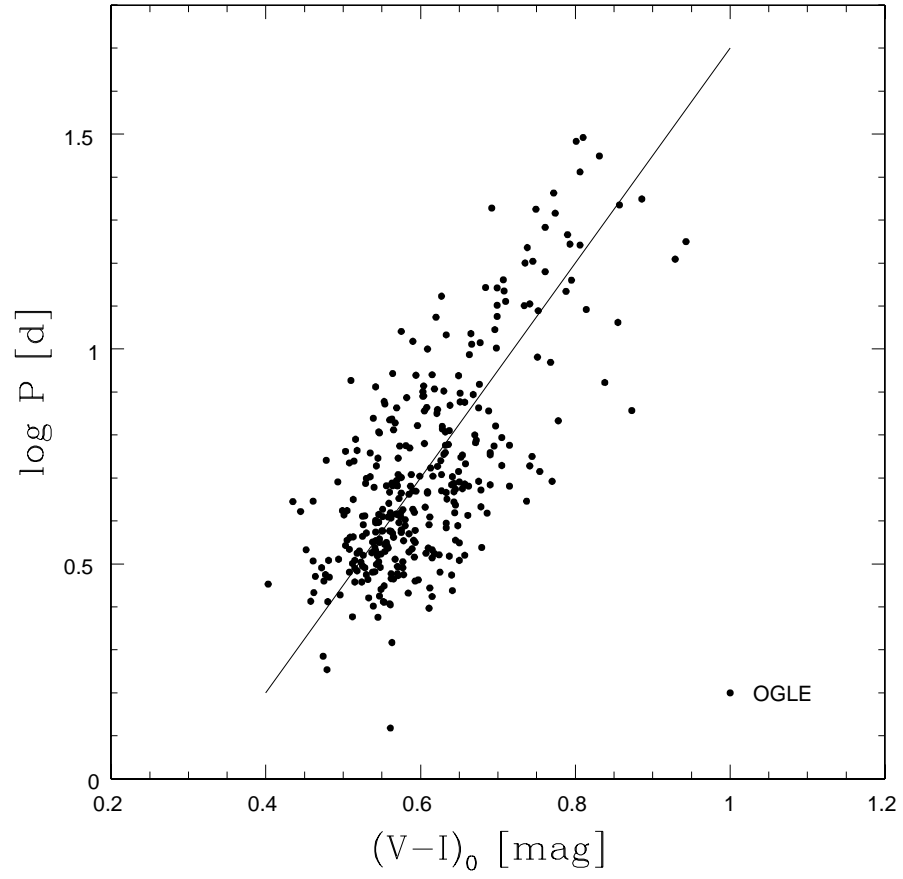
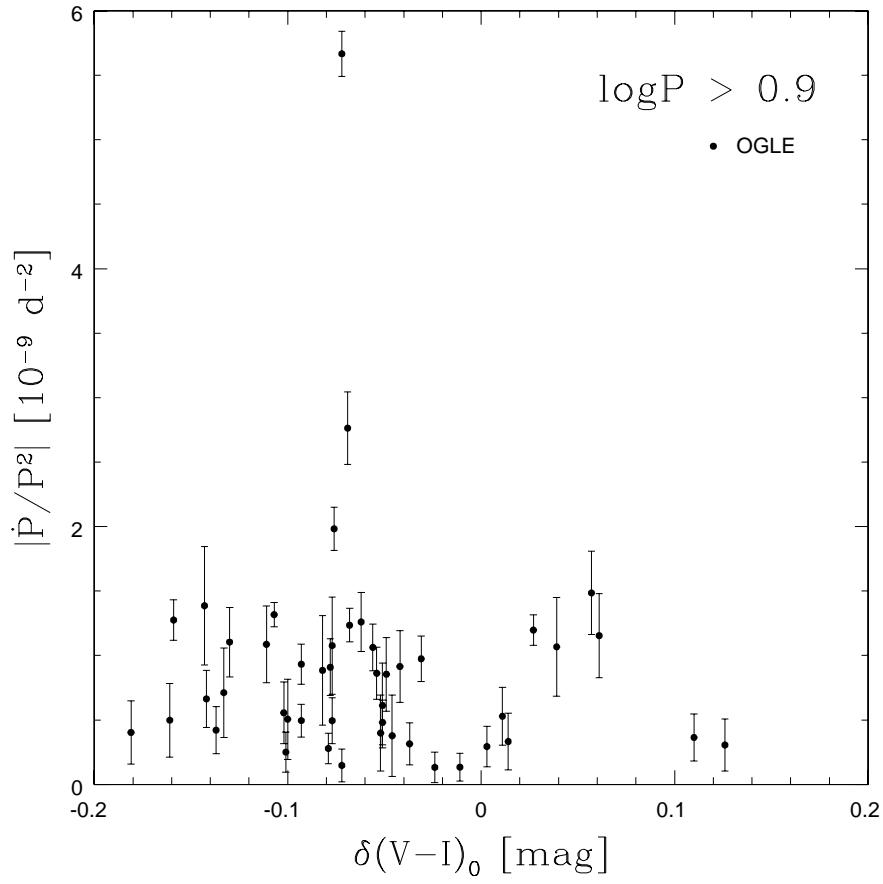Fig. 8.   The observed color-period relation for the OGLE fundamental mode Cepheids.

Fig. 9.   The dependence of the observed rate of Cepheid period change as a function of color difference between the observed value $(V-I)_0$ and the line shown in Fig. 8.